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Electricity Enhancement and Thermal Energy Production from Concentrated Photovoltaic Integrated with a 3-Layered Stacked Micro-channel Heat Sink

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Abstract. The thermal effectiveness of three types of heat sink has been investigated experimentally using a flexible kapton heater to simulate the generated heat from a CPV system for various heating loads. The three heat sinks are an air cooled flat aluminum heat sink, an air cooled finned aluminum heat sink and a water cooled 3-layered stacked micro-channel heat sink. It is shown that the temperature of the heater surface is reduced dramatically by using the finned heat sink compared to the flat plate heat sink. Also, the 3-layered stacked micro-channel heat sink is able to reduce the heater surface temperature below 50°C for 5.5W heater power. The work also studies numerically the effect of the 3-layered stacked micro-channel heat sink in a single solar cell receiver for a 500× concentration in enhancing the solar cell electrical efficiency and production of the thermal energy. The study uses a three dimensional modelling approach for real weather conditions. The results show a high solar cell electricity performance.

INTRODUCTION

Nowadays, Concentrating Photovoltaic (CPV) technology is considered as another option for solar electricity generation along with the conventional flat plate PV technology especially in high direct normal irradiance areas [1]. Increasing the solar irradiation falling on the CPV increases its electrical production. At the same time, the increase of the concentration ratio causes more heat generation by the CPV system and exhibits higher temperature. The increase of solar cell temperature will result in a decrease of its efficiency in the order of ~0.051% per °C and can cause long-term degradation if it exceeds the maximum temperature limit [2]. Therefore, any CPV system usually requires a cooling system to ensure that solar cells do not exceed the allowable temperature upper limit.

The CPV system is usually thermally regulated using two approaches, passive and active. The passive approach usually uses the natural convection phenomena and requires no mechanical equipment to circulate the air. It could be very simple such as using a simple flat plate or more complicated such as air cooled micro-channel fins [1] and using the phase change materials [3-9]. The active cooling approach uses mechanical equipment such as fans and pumps to circulate the coolant fluid. Various active cooling methods have been proposed such as air circulation, water circulation and fluid immersion techniques. Densely packed solar cell arrangement is a group of solar cells packed together and a large area focuses the concentrated rays onto the solar cells [10]. One of the challenges of this configuration is the cooling system due to the space restrictions. Royne et al. [11] have pointed that the passive cooling cannot be used in the densely packed configuration.

A stacked micro-channel heat sink technique is considered as one of the most efficient active cooling techniques in terms of pumping power and heat removal capability [12]. Al Siyabi et al. [13] are the first to use the multi-layers stacked micro-channel in the CPV cooling applications. The study has investigated numerically the multi-layers stacked micro-channel heat sink for a single CPV receiver. The effects of number of layers and channel geometry on the solar cell temperature and the fluid pumping power are evaluated. The results show that the solar cell temperature, thermal resistance and fluid pumping power reduce as the number of layers increases. Also, increasing the channel height leads to a decrease in the pressure drop along the channel.

The objective of this paper is to present a further analysis of the multi-layers stacked heat sink in CPV applications using both the experimental and numerical approaches. In the first part of the study, a proposed 3-layered stacked micro-channel heat sink will be compared experimentally to various other conventional cooling techniques of using a flat aluminum plate and micro-channel heat sink using natural convection. A further analysis of 3-layered stacked micro-channel heat sink in CPV applications using numerical approach will be carried out. The analysis will include the overall system efficiency (electrical and thermal) for a specific location with high beam solar radiation.

EXPERIMENTAL AND NUMERICAL PROCEDURES

The combined experimental/numerical study is undertaken to investigate the thermal behavior of a single solar cell CPV using different cooling techniques as follows:

- An experimental setup is constructed to compare three cooling techniques: aluminum plate, finned aluminum plate and 3-layered stacked micro-channel heat sink with different heat source rating.
- A 3D model of CPV integrated with 3-layered stacked micro-channel heat sink is developed with COMSOL software which considers the actual weather conditions of Jaipur in India for a typical cloudless day in June.

Experimental Setup and Test Procedure

As it is mentioned earlier, the objective of this section is to compare the performances of three different cooling techniques. The three cases are: flat aluminum plate (case A), finned aluminum plate (case B) and 3-layered stacked heat sink for the water cooling (case C). In all cases, a kapton heater is used to simulate the heat load in the CPV system. The heater size is 10mm×10mm having rated maximum power of 5.5W.

The experimental setup as shown in figure 1 is used for the air cooled heat sink investigations (cases A & B). It consists of a kapton heater attached to the testing plate using 3M adhesive. The aluminum plate dimensions of case A are 30mm×32mm×2mm whereas the dimensions of case B are shown in figure 1: $L=30\text{mm}$, $W=32\text{mm}$ and $W_c=W_f=h_f=t_b=1\text{mm}$. A variable DC power supply is used to control the power input to the heater. K-type thermocouples are used to measure the temperature of the heater surface, upper side of the aluminum plate and the ambient temperature. A temperature logger (Keithley 2700) is used for temperature-recording with an interval of 10s. The experiment is stopped when the system reaches its steady state. The experiment setup is placed in a temperature controlled room at temperature of 23°C.

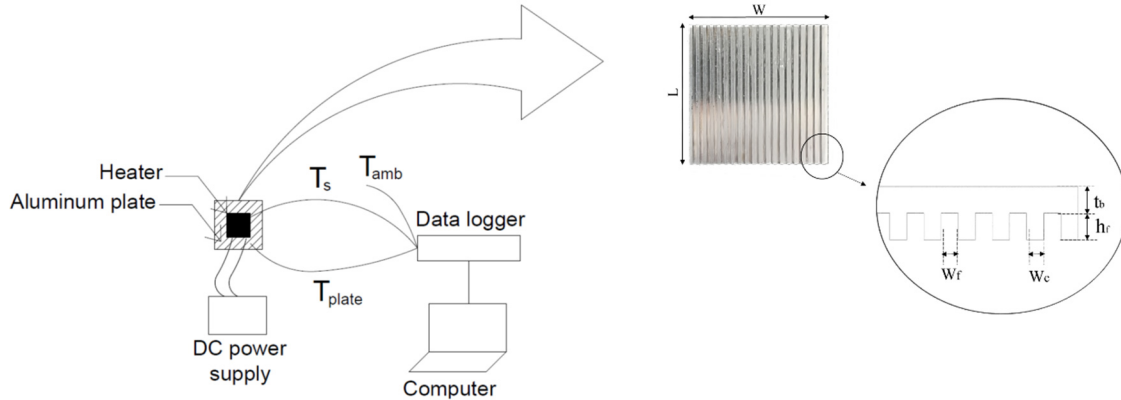


FIGURE 1. Schematic of the experimental setup for cases A & B.

Case C is tested using the experimental setup shown in figure 2. It is composed of the heat sink testing section, a heating circulation bath, a flowmeter and various K-type thermocouples with a data logger. The heater is attached at the center of the top layer using the 3M adhesive. The dimensions of the plates are similar to that of case B and are stacked in an acrylic transparent case manufactured at the in-house campus workshop. A rubber sealing is used to seal the case to avoid any water leakage and finally bolts are used to ensure no leakage during the experiments. Constant water temperature is supplied using the heating/cooling circulation bath at a temperature of 23°C. Then, water is circulated in the heat sink with a measured volume flow rate using the variable area flowmeter and controlled with a

valve at the inlet. K-type thermocouples are placed to measure the temperature of the heater surface, top plate temperature and outlet water temperature. The temperature is recorded with an interval of 10s until the steady state is reached.

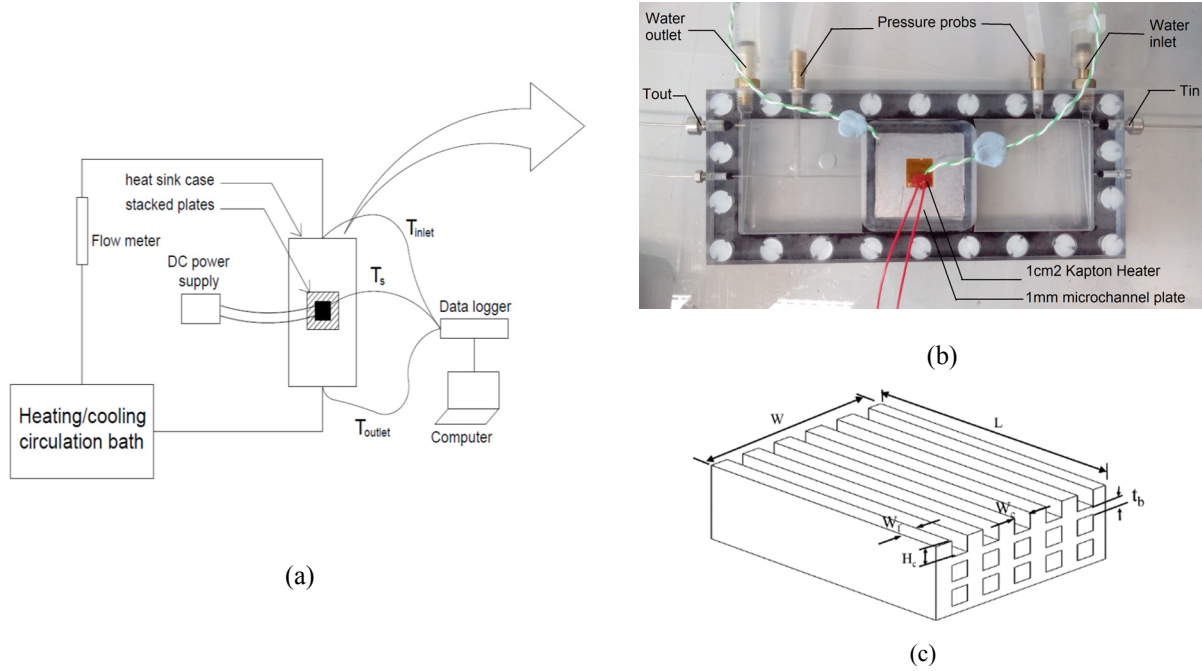


FIGURE 2. (a)Schematic of the experimental setup for case C, (b) photograph of the 3-layered stacked microchannel heat sink and (c) Schematic of the 3-layered microchannel plates.

Numerical Modelling

As it is explained earlier, the modelling work is to analyze the behavior of the 3-layered stacked micro-channel heat sink integrated with a CPV multi-junction solar cell assembly (Azurspace 3C42) in real ambient conditions. A three dimensional modelling of the system is performed using non-isothermal flow physics. The simulations are conducted in time dependent conditions. The CPV receiver dimensions and its thermophysical material properties are similar as in the previous work [13]. The following assumptions have been considered:

- The solar cell is subjected to a uniform solar radiation with a concentration ratio of $500\times$ and all heat is produced by the Ge subcell [14].
- The ambient temperature is considered similar to the real data.
- Water is selected as the coolant fluid and its properties vary with temperature. Water is assumed to be supplied from a tank with a constant temperature of 29.2°C throughout the day.
- Water total mass flow rate is 3.32×10^{-4} kg/s and the flow is steady, laminar and fully developed.
- The solar cell electrical efficiency and dissipated heat are presented using equations 1 and 2 respectively:

$$\eta_{elec}(T) = 0.40227 - 5.09 \times 10^{-4} T \quad (1)$$

$$Q_h = (1 - \eta_{elec})Q_o \quad (2)$$

Where T is the solar cell temperature between 25°C and 80°C , Q_o indicates the total optical power in W at the surface of the solar cell and η_{elec} is the electrical efficiency of the solar cell. The optical power takes into account both the concentration ratio and the concentrator efficiency.

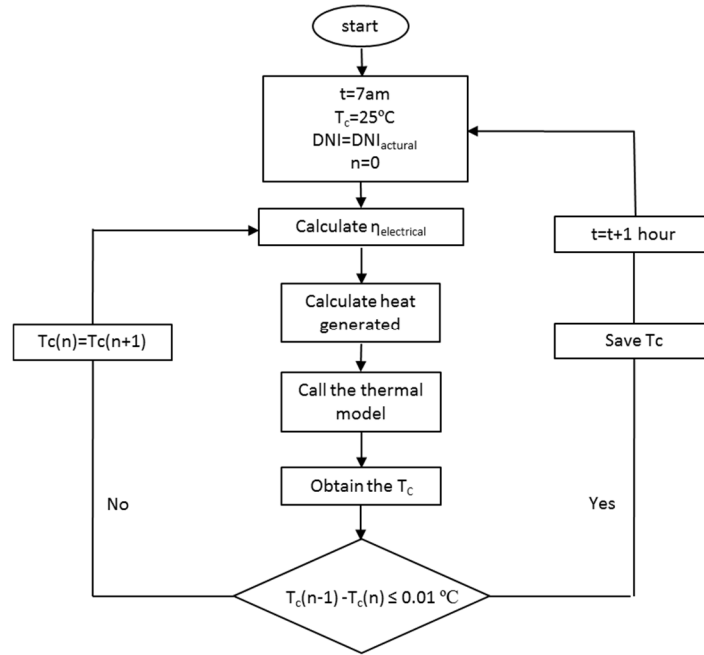


FIGURE 3. Flowchart of the numerical solution.

Coupling both the electrical and thermal models is very important in CPV because of the effect of the solar cell temperature on the electrical efficiency and the amount of heat generated by the solar cell. So, the simulations are carried out in two stages. In the first stage, the solar cell efficiency is computed for steady state conditions for each hour based on the flowchart shown in figure 3. A trial and error iteration approach has been used to find the solar cell temperature at the steady state condition, the solar cell temperature being initially assumed equal to 25°C. Equations (1) and (2) are used to find the solar cell efficiency and the generated heat by the solar cell respectively. In the second stage, the model is simulated for real non-steady state conditions by using the solar cell electrical efficiency obtained from the first stage.

RESULTS AND DISCUSSION

Comparison of Passive and Active Cooling Techniques

Figure 4 shows the variation of the heater surface temperature with the input power for the three cases; A, B and C. As expected, the heater surface temperature increases as the applied power to the heater increases. The increase of temperature depends on the type of the heat sink. For instance, when the heater power is increased from 2.75W to 5.5W, the temperature increases by 43.7%, 152.6% and 41.6% for the heat sink in case A, B and C respectively. Also, the results show that using aluminum plate as heat sink (case A) is not recommended even at low heat load (2.75W) where the heater temperature reached to 180°C. In addition, the finned heat sink (case B) might be suitable for heat loads up to 4W where the temperature is maintained just under 110°C. The 3-layered stacked micro-channel heat sink (case C) is able to maintain the surface temperature below 55°C for the heater load up to 5.5W which is less than the maximum solar cell temperature recommended by the studies.

Thermal resistance is one way to evaluate the overall thermal performance of microchannel heat sink and it measures the difficulty that heat sink faces in dissipation of heat to fluids. The total thermal resistance of the heat sink (R_{tot}) is defined as the ratio between the maximum temperature difference and the applied heat flux [15]. The calculated thermal resistances for the 5.5W heating power are 43.1, 36.2 and 5.6 cm².K/W for the cases A, B and C, respectively. This shows that the multi-layered heat sink has a great influence on reducing the thermal resistance as compared to the other two cases.

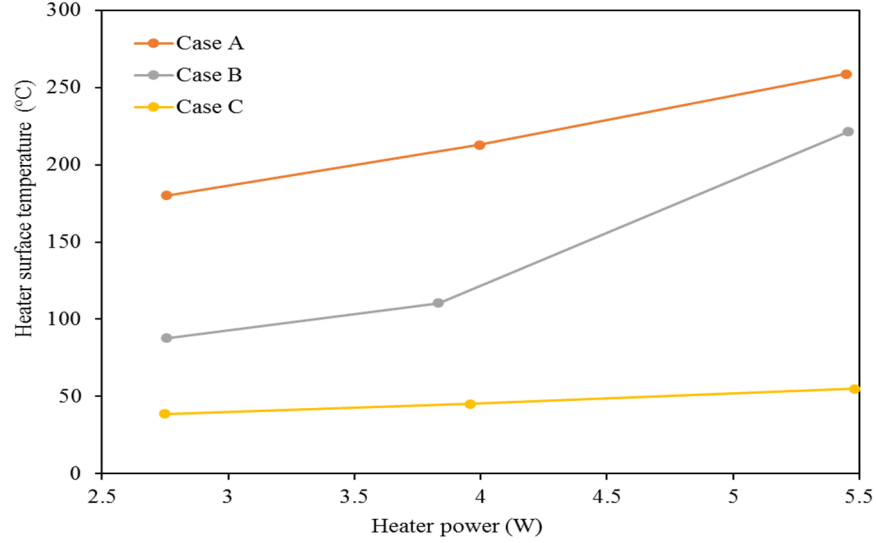


FIGURE 4. Heater surface temperature at different heater powers for various heat sink arrangements.

3-layer Stacked Micro-channel Heat Sink for Jaipur, India

In this section, the numerical results are presented. The real weather conditions for a typical cloudless day in June at Jaipur ($26^{\circ}49'$, $75^{\circ}48'$) are chosen for this study. Figure 5 shows the weather conditions included the global, direct and diffuse solar radiation and the ambient temperature. The direct solar radiation varies throughout the day and reaches its peak between the 12 and 13 of 630W/m^2 .

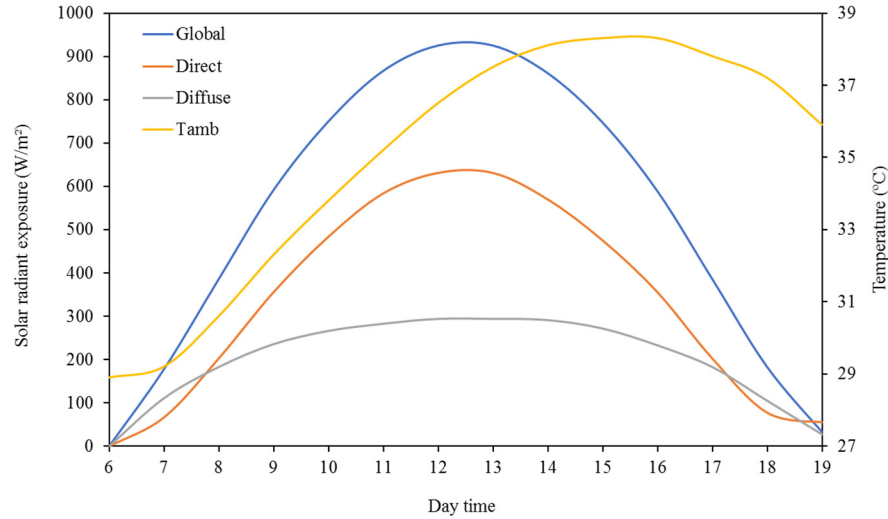


FIGURE 5. The measured solar irradiance and ambient temperature data for typical cloudless day in June in Jaipur, India [16].

Figure 6 shows the variations in the solar cell temperature with iterations for the 3-layered stacked micro-channel heat sink for the channel size of $1000 \times 1000 \mu\text{m}$ at different hours of the day using the steady state approach. It is noted that the temperature difference between the successive iterations remains lesser than 0.01°C after the 3rd iteration in all simulations. Also, the temperature of the solar cell is managed under 50°C throughout the day.

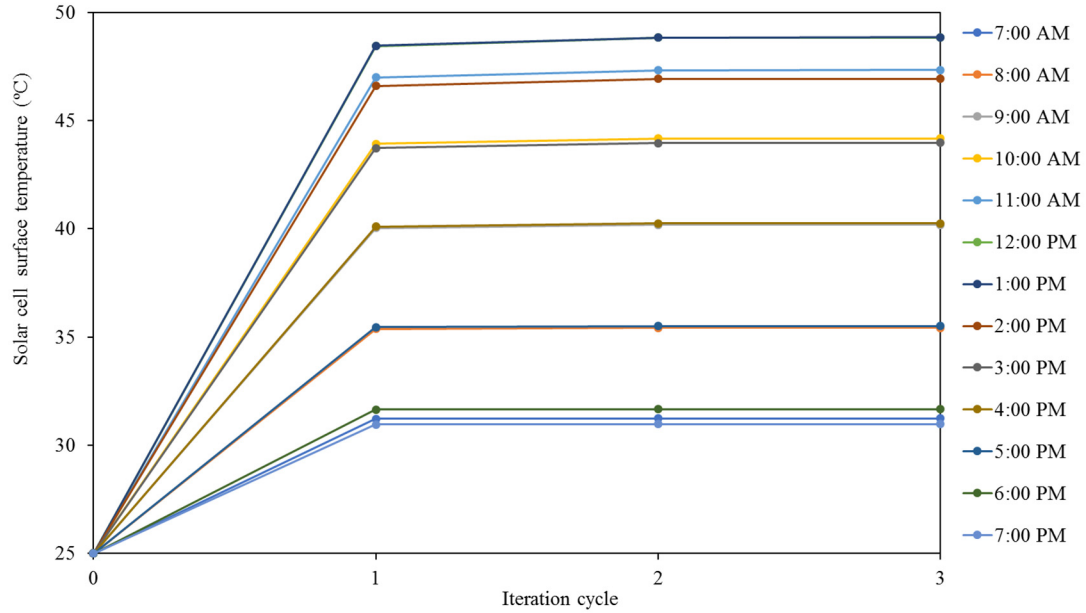


FIGURE 6. Variation of solar cell average temperature with iterations for the 3-layer stacked micro-channel heat sink for 3.32×10^{-4} kg/s water flow rate for each hour during the day.

The electrical performance of the solar cell is shown in figure 7(a). It is noted that the solar cell electrical performance varies between 40.25% and 41.2% using the 3-layered stacked micro-channel heat sink. In figure 7(b), the water outlet temperature and the heat collected by fluid are plotted versus the day time. The figure shows that the temperature of the outlet water increases during the day and reaches its maximum temperature of 43°C at 12:30 and then it starts decreasing. Also, the thermal efficiency of the system is approximated by 28.2% of a total heat of 23.8MJ during the day.

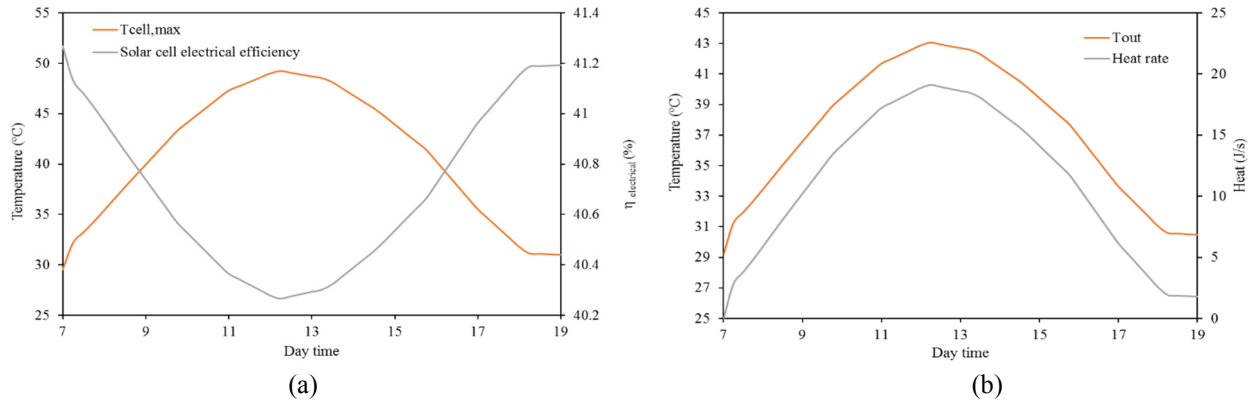


FIGURE 7. The 3-layer stacked micro-channel heat sink, (a) the solar cell electrical efficiency and temperature versus time, (b) Water outlet temperature and heat rate extracted by fluid versus day time

CONCLUSIONS

In this paper, the concept of multi-layer micro-channel heat sinks for CPV applications has been studied both experimentally and numerically. In the first section, the study has compared the conventional air cooled heat sinks with 3-layered stacked micro-channel heat sink using the experimental approach. In the second section, the study has investigated the behavior of CPV single solar cell receiver integrated with the 3-layered stacked micro-channel heat sink using the numerical approach. The experimental results show a high increase in the heater surface temperature when using the conventional heat sinks where the temperature is ranged between 87.5°C and 221°C for the heater

input power ranging between 2.75W and 5.5W respectively. Moreover, the 3-layered stacked micro-channel heat sink is able to reduce the heater surface temperature to the safe range of solar cells working conditions. The investigation of the thermal behavior of the proposed stacked heat sink under real weather conditions has been explored by coupling the electrical and thermal models. The results show a solar cell electrical efficiency of 40.7% variation of less than 1% within the day time and thermal efficiency of 28.2% where the solar cell temperature is maintained below 50°C.

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